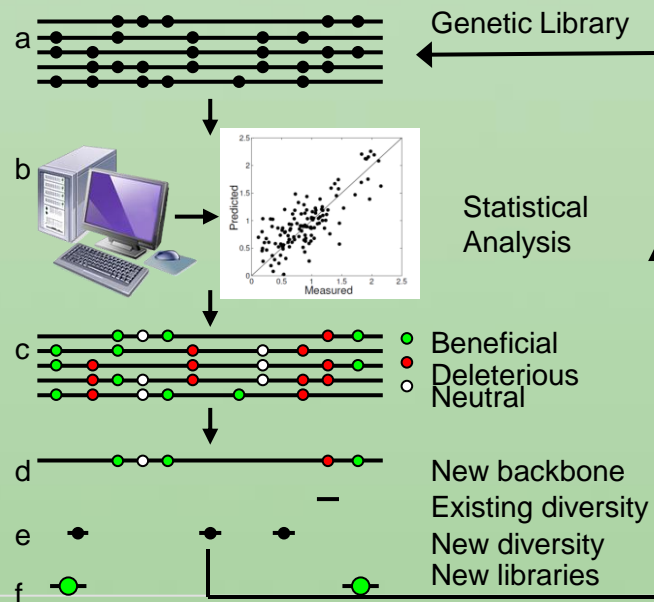
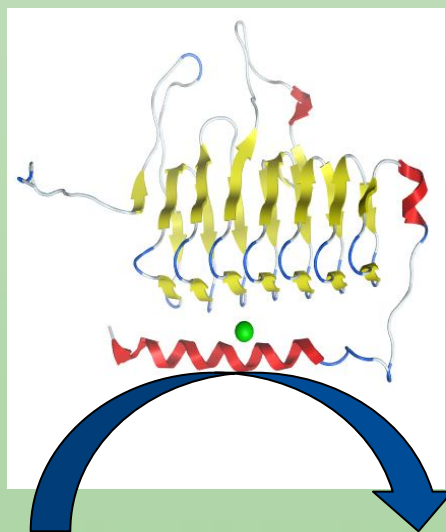


Low-Cost Biocatalyst for Acceleration of Energy Efficient CO₂ Capture



Problem:

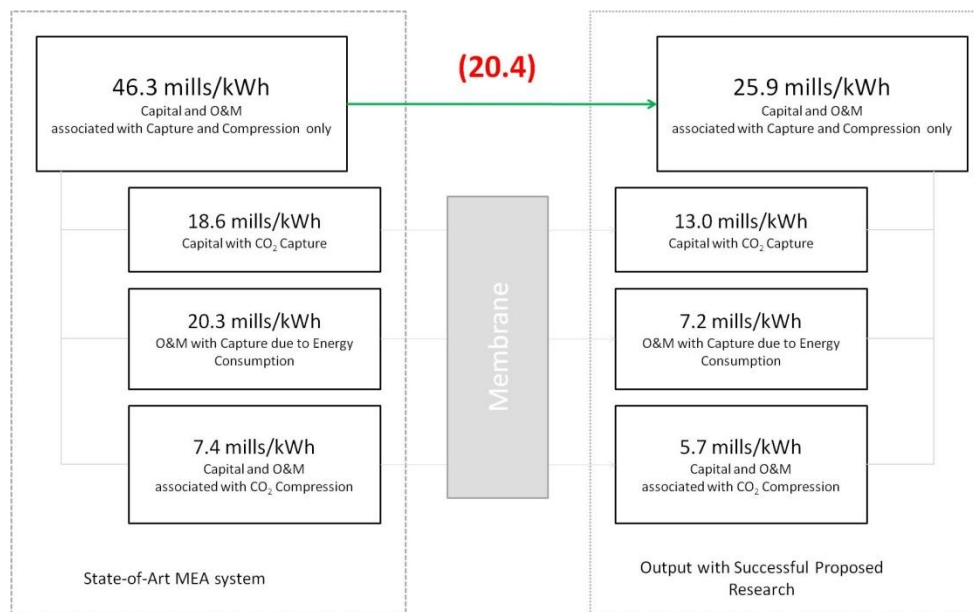
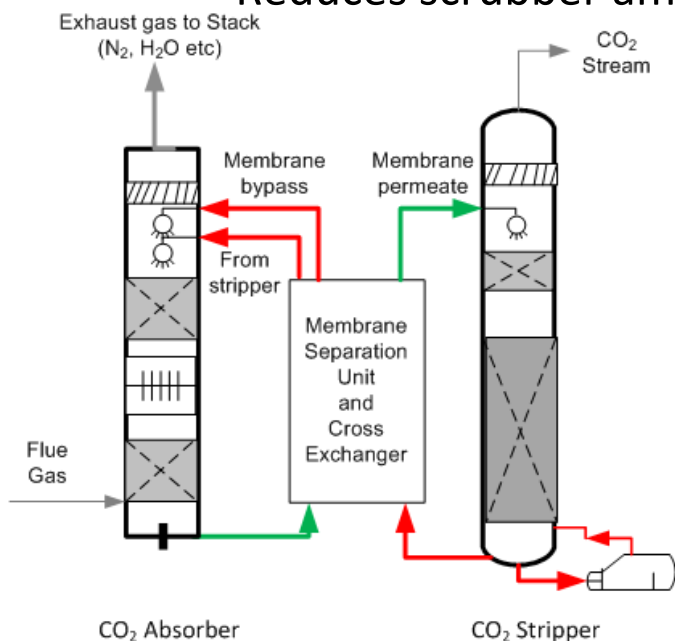
- Solvents such as monoethanolamine have high parasitic energy losses

Solution:

- Use Carbonic Anhydrase to accelerate CO₂ capture in solvents with favorable thermodynamics, but slow absorption kinetics
- Use state of the art Directed Evolution technology, demonstrated in chemical manufacture, to create forms of CA active and stable under CO₂ capture conditions

Reduce the energy penalty associated with solvent-based post combustion CO₂ capture with a catalytic membrane

- Increased carbon loading
 - Water reduced in the solvent by physical separation
 - Catalytic reaction increases bicarbonate concentration
- Lower NH₃ solvent concentration permissible
 - Membrane concentration reduces stripper load
 - Reduces scrubber ammonia loss

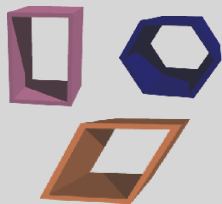


High-Throughput Synthesis

Highly-parallel, automated discovery of new MOFs



Automated Solid and Liquid Dosing



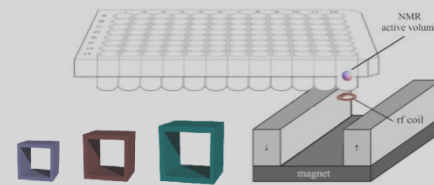
New Structure Types

High-Throughput Characterization

Rapid identification of new porous materials



Powder X-ray Diffraction

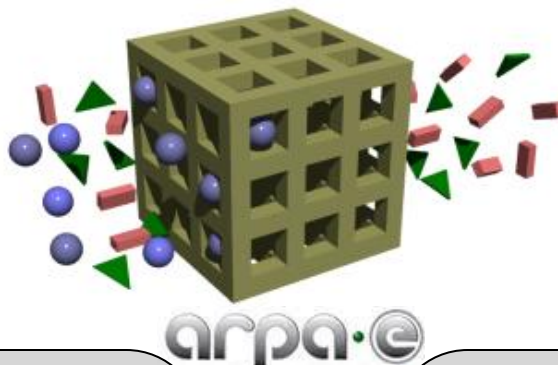


NMR Porosity Screening



Maciej Haranczyk
Jeffrey R. Long
Eric R. Masanet
Jeffrey A. Reimer
Berend Smit

High-Throughput Discovery of Robust Metal-Organic Frameworks for CO₂ Capture



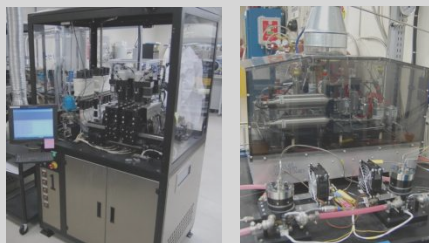
Steven S. Kaye



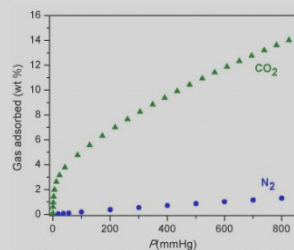
Abhoyjit S. Bhowm

CO₂ Adsorption Screening

Rapid screening of CO₂ capture performance



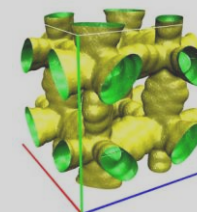
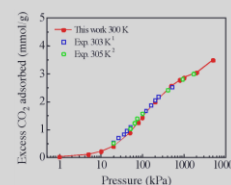
High-throughput Instrumentation



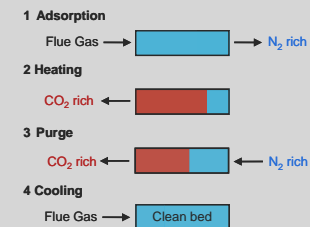
Adsorption Data

Computational Analysis

Data analysis, life cycle and sorbent performance analysis



Simulations



Sorbent Performance

CO₂ Capture with Ionic Liquids Involving Phase Change

Prof. Joan F. Brennecke/ University of Notre Dame

Technology Summary

A new concept for CO₂ capture that uses *phase change ionic liquids (PCILs)* offers the potential to significantly reduce parasitic energy losses incurred from capturing CO₂ from flue gas. PCILs are solid ionic materials that have high CO₂ uptake (one mole of CO₂ for every mole of salt at post-combustion flue gas conditions) and form a liquid when they react with CO₂. This allows for a novel process that uses the heat of fusion to provide part of the heat needed to release CO₂ from the absorbent, reducing the total energy required. This project will (1) develop and characterize PCILs; (2) evaluate energy savings in a new CO₂ capture process; and (3) demonstrate the technology at laboratory scale.

Key Personnel

ND: Joan F. Brennecke, Edward J. Maginn, Mark J. McCready, Patrick Murphy, William F. Schneider
MATRIC: George Keller

Program Summary

Period of performance: 36 months

	Key Milestones & Deliverables
Year 1	<ul style="list-style-type: none">Characterization of first set of PCILs (TRL 3)Identification of key process variables
Year 2	<ul style="list-style-type: none">Detailed process model based on theoretical and experimental resultsGo/NoGo based on predicted parasitic energy
Year 3	<ul style="list-style-type: none">TRL 4 demo of PCIL based CO₂ capture process

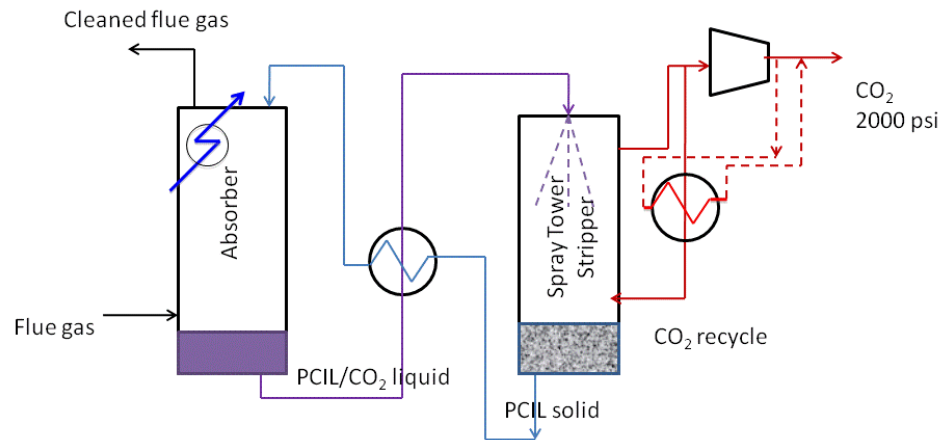
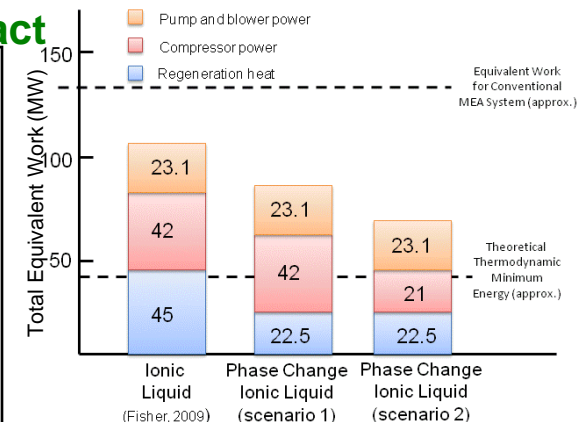
Technology Impact

In a 500 MW (471 MW de-rated) coal plant:

Aqueous amine scrubbing incurs parasitic energy losses of 28% (132 MW).

Current ILs could reduce energy losses to 23% (110 MW)

Proposed PCIL process could reduce energy losses to 14% (66 MW)!



Radically Reducing the Cost of Carbon Capture

Participants

Sustainable Energy Solutions, American Air Liquide, GE Global Research, Brigham Young University.

Objective

To perform a detailed systems analysis, cost of electricity estimates, develop operational prototypes of key components, and provide a conceptual design for a skid-scale demonstration.

Advantages of CCC over Traditional Absorption Systems

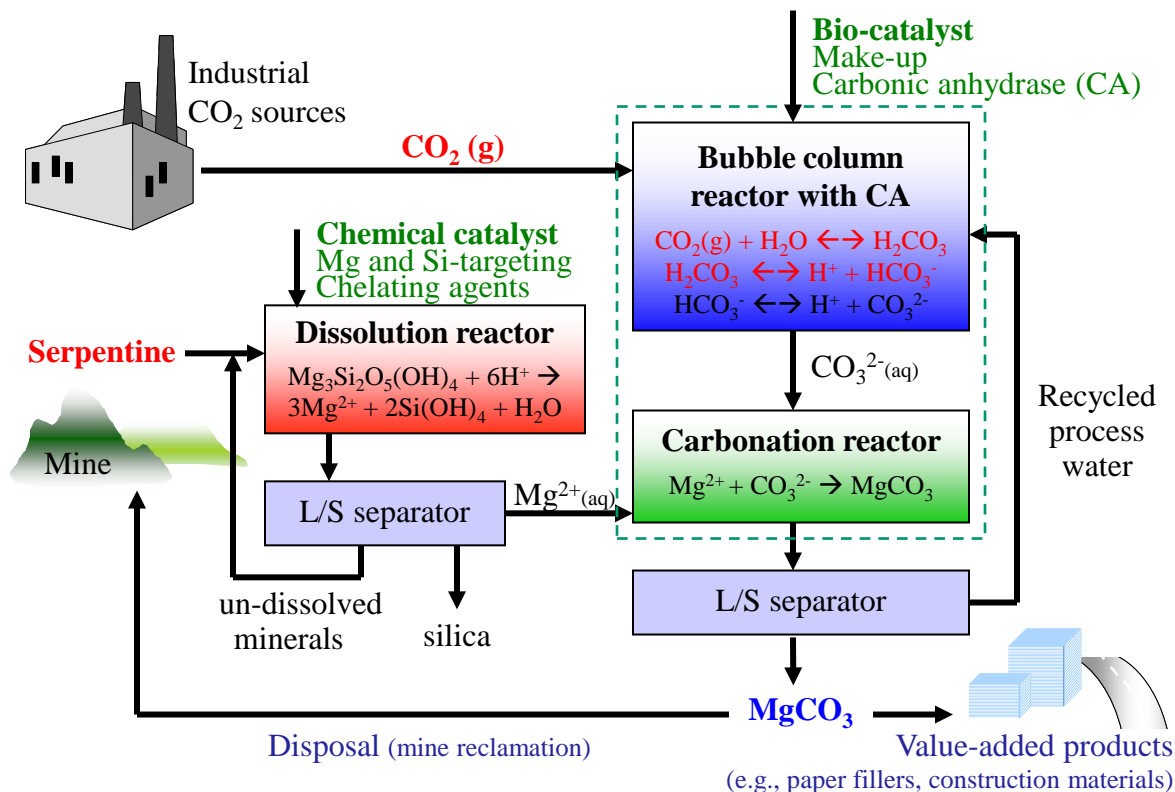
- Pollutant removal (i.e. SO_2 , NO_2 , HCl , and Hg)
- Retrofit/bolt-on technology
- 40%+ lower cost of electricity
- 50%+ lower parasitic load
- 99%+ CO_2 capture
- ~5MM tons/yr of useable water recoverable

Chemical and Biological Catalytic Enhancement of Weathering of Silicate Minerals as Novel Carbon Capture Storage Technology

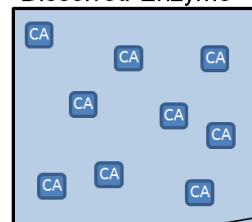
Ed Swanson¹, Tushar Patel¹, Scott Banta¹, Pat Brady², Kevin Davis³ and Ah-Hyung Alissa Park¹ (PI)



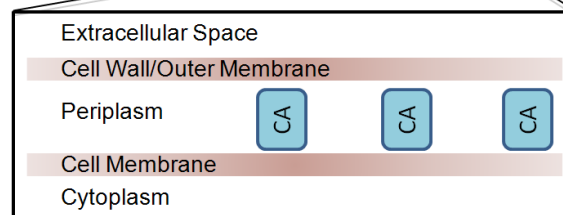
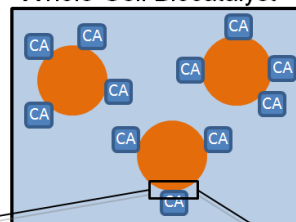
Schematics of the proposed engineered mineral weathering process



Scheme 1:
Dissolved Enzyme



Scheme 2:
Whole-Cell Biocatalyst



	Key Milestones & Deliverables
Year 1	<ul style="list-style-type: none"> Synthesis of chemical and biological catalysts for enhanced weathering of silicate minerals
Year 2	<ul style="list-style-type: none"> Evaluation of developed catalysts under industrial operating conditions (i.e. flue gas)
Year 3	<ul style="list-style-type: none"> Process integration & system engineering for process intensification for economic feasibility

Technology Summary

State of the Art: Aqueous amine-based solvent systems for post-combustion CO₂ capture from power-plant flue gas use low-pressure steam for regeneration, consuming 2.8-3.5 GJ/tonne of CO₂ and increasing the cost of electricity by 60-80% and the cost of CO₂ avoided to \$70/ton.

Proposed Technology: Novel non-aqueous solvents exploiting different CO₂-solvent chemistry to reduce regeneration energy for CO₂ capture to ≤ 2 GJ/tonne of CO₂ by reducing the sensible heat (lower sensible heat and regeneration temperature) and regeneration energy (energy to release the CO₂).

Key Personnel

RTI International: Luke Coleman, Marty Lail, Steven Reynolds
BASF Corp.: Todd Spengeman, Georg Sieder
 BASF is a worldwide leader in solvent technology for CO₂ capture

Program Summary

Period of performance: 36 months

Technology Development Plan

Transitioning from novel solvent concept to commercial process

	Previous Work			Current Project		Future Development			
Yr	2009-10			2010-13		2014-15		2016-18	2019+
TRL	1	2	3	4	5	6	7	8	9

Proof of Concept/Feasibility

Prototype Testing at Power Plant

Laboratory Validation

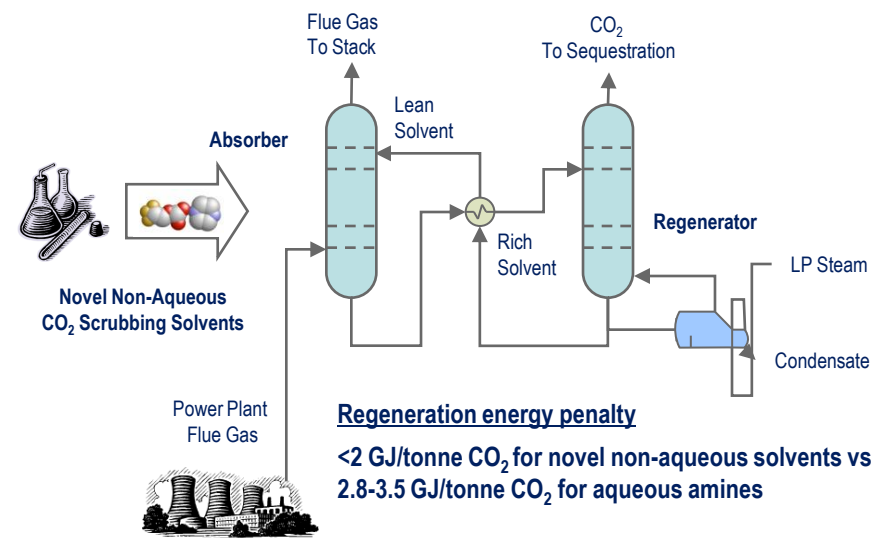
- Comprehensive solvent screening
- CO₂ capture process modeling

Relevant Environment Validation

- Bench-scale testing to assess solvent performance
- Techno-economic analysis
- Preliminary engineering design package for a pilot unit

Technology Impact

- Advanced cost-competitive CO₂ capture technology capable of capturing 1.4 billion tonnes of CO₂ per year from coal-based power generation plants with < \$45/ton cost of CO₂ avoided.
- Deployment of this technology will lead to new domestic business and job opportunities in solvent manufacturing, engineering, and construction.



Develop non-aqueous solvent system(s) for post-combustion CO₂ capture achieving 90% CO₂ capture with ≤ 2 GJ/tonne CO₂ regeneration penalty and cost of CO₂ avoided of < \$45/tonne



Development of Stimuli Responsive Metal-Organic Frameworks for Energy Efficient Post-Combustion CO₂ Capture



Hong-Cai (Joe) Zhou, Hae-Kwon Jeong and Perla Balbuena, Texas A&M University

The goal of this work is to develop innovative metal-organic framework-based molecular sieves whose adsorption and desorption properties can be finely tuned for energy-efficient post-combustion CO₂ capture.

Stimuli Responsive Sorbents

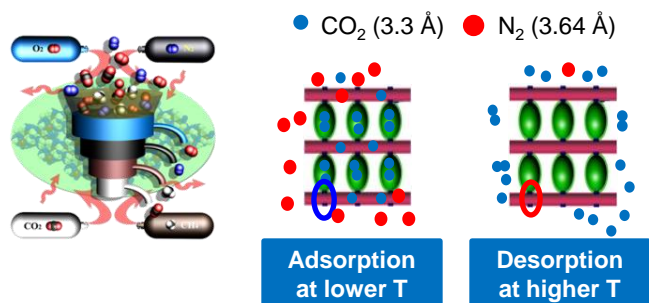


Figure 1. Conceptual illustrations of MAMS applications as stimuli-responsive sorbents.

Stimuli Responsive Membranes

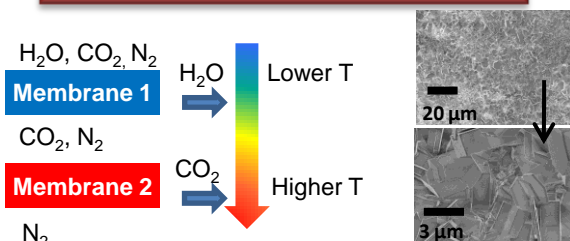


Figure 2. MAMS membranes conceptual illustration and preliminary results.

Mesh-Adjustable Molecular Sieves (MAMS)

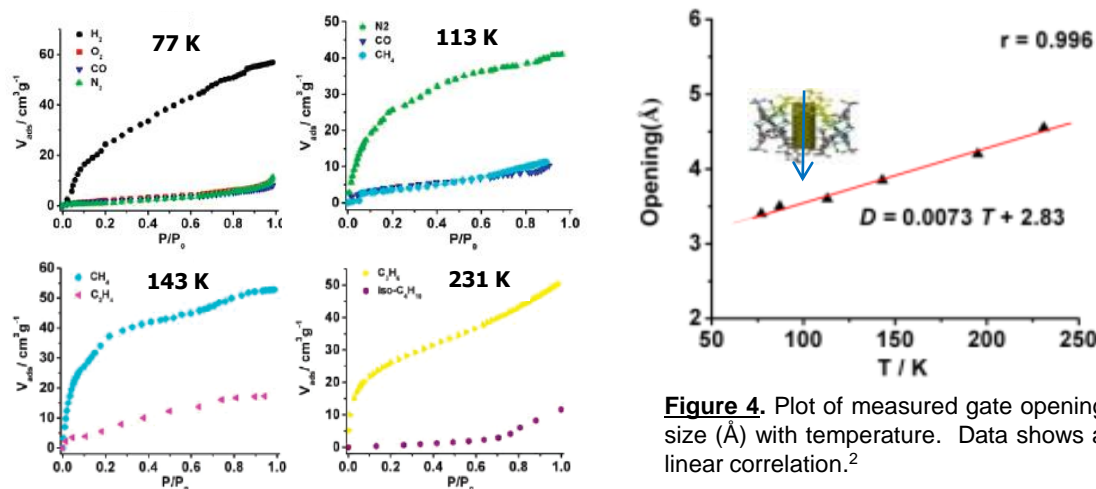


Figure 3. MAMS gas adsorption isotherms²

Simulation of MAMS

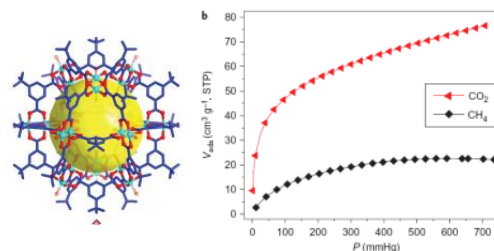


Figure 5. Metal-organic polyhedra – a part of MAMS frameworks which exhibits selective adsorption.³

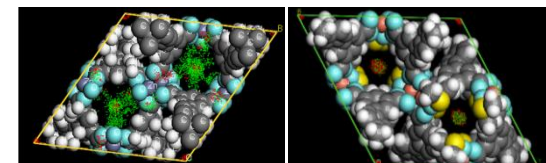


Figure 6. Preliminary GCMC simulations of a 20/80 mixture of CO₂ and N₂ at 233K and 1000 kPa on MAMS-2 (left) and MAMS-5 (right).

References

- [1] Yaghi, O.M. et al, *Nature*, **2003**, 423, 705-714.
- [2] Zhou, H.-C. et al, *J. Am. Chem. Soc.* **2009**, 131, 6445-6451.
- [3] Li, J.-R.; Zhou, H.-C. *Nature Chem.* **2010**, in press.

Electrochemically Mediated Separation for Carbon Capture and Mitigation

T. Alan Hatton, Howard J. Herzog, Fritz Simeon, Thomas Hammer, Harald Landes
Massachusetts Institute of Technology and Siemens AG

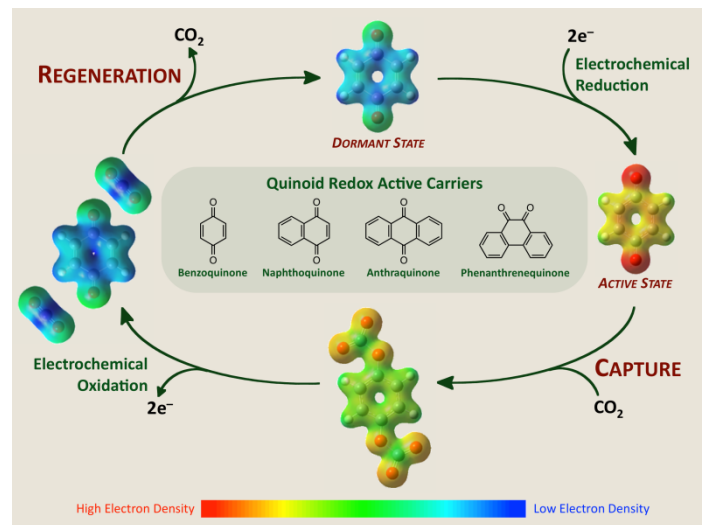
Electrochemically mediated separation (ECMS) processes are to be developed and assessed for post-combustion CO₂ capture.

Significant changes in the binding affinity, selectivity and capacity for CO₂ of **redox-active sorbents** on changes in their redox state will be exploited.

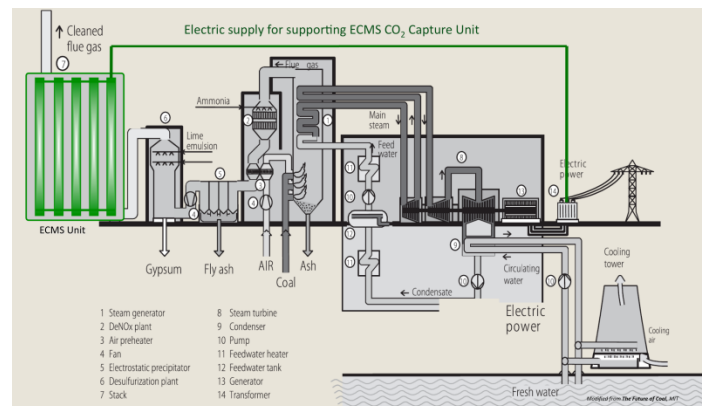
Electrical energy is to be utilized to facilitate effective CO₂ capture under more benign, isothermal conditions of sorption and desorption than in traditional continuous chemical-scrubbing operations.

The project will entail molecular modeling and experimental optimization of **carrier structure**, fabrication and evaluation of **prototype separation units**, and **techno-economic evaluation** of this potentially transformative technology for carbon capture system.

Electrochemistry of CO₂ Sorbents



Integrated Electrochemical CO₂ Capture Unit with Fossil Fuel-Fired Power Generator



Key Milestones & Deliverables

Synthesis and optimization of carriers
Initial ECMS CO₂ cell design/construction
Computer simulation of ECMS cell

Prototype ECMS CO₂ cell tests
Techno-economic assessment of ECMS
Cycle analysis of ECMS system

Year 1

Year 2

CO₂ Capture Process Using Phase-Changing Absorbents

Program Team



GE Global Research

- Material Development
- Unit Op Design/Testing



GE Energy

- Modeling, and Design of Integrated Energy Systems
- Economic Analysis

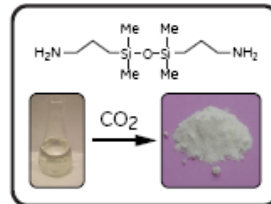


University of Pittsburgh

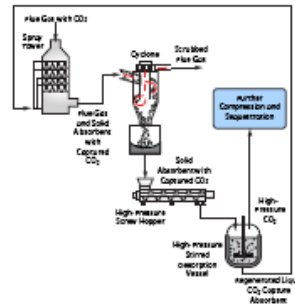
- Absorption Testing of Materials
- Property Measurement

CO₂ Capture Process Using Innovative Phase-Changing Absorbents, 2 -Year, \$3.8M

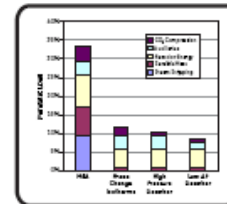
Program Objective: To develop a cost-efficient process that utilizes a CO₂-capture absorbent that reversibly transforms from a liquid to a solid upon reaction with CO₂ to remove CO₂ from flue gas derived from pulverized coal fired power



Material Advancement



Process Development



Plant and Process Modeling

Technical Approach

- Optimize advanced phase-changing absorbent
- Design innovative process integrating absorption of CO₂, transfer of solid material, and desorption of CO₂ under pressure
- Develop and optimize plant and process modeling for unique CO₂ capture process

Program Deliverables

- A material and CO₂ absorption/desorption process that results in <10% parasitic power load and <\$25/ton of CO₂ avoided

Anticipated Benefits of the Proposed Technology

- Eliminate 1 billion tons of CO₂ emissions from PC power plants
- Increase energy security with market for domestic coal
- U.S. leads CO₂ capture technology
- Increase energy efficiency for CO₂ capture vs. MEA
- Create jobs in construction and manufacturing

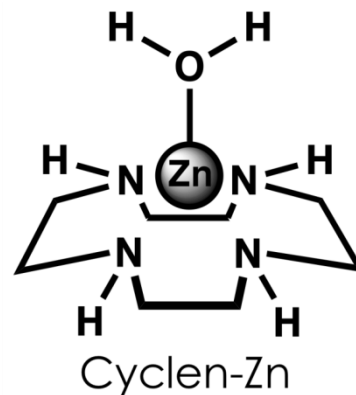
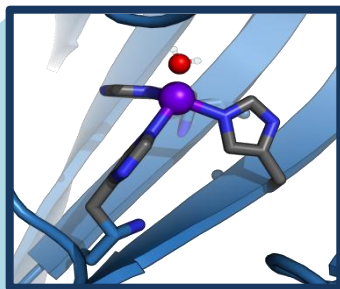
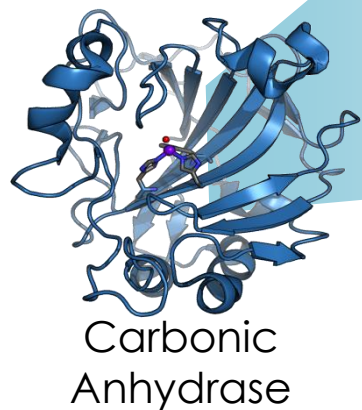


imagination at work

Small-molecule bio-mimetic catalysts for carbon capture

Lawrence Livermore National Laboratory, Babcock & Wilcox Co.,
and the University of Illinois at Urbana-Champaign

⇒ Integrated, interdisciplinary development
process from molecular design to pilot scale
testing

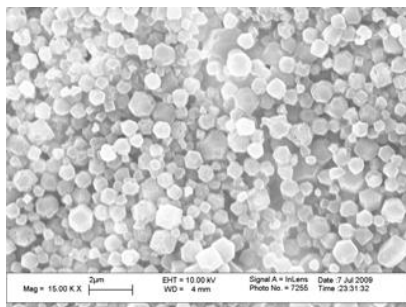
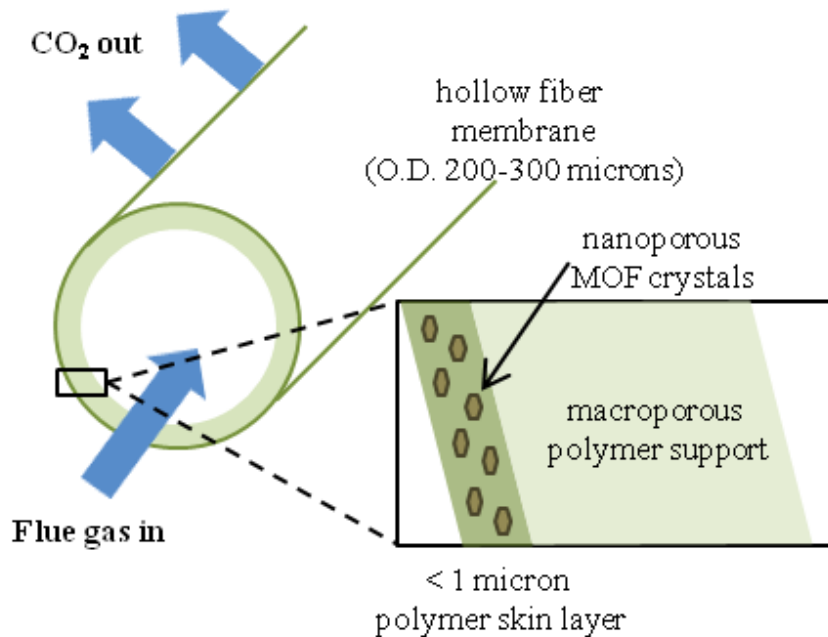


Objectives:

- Harness the features of a natural enzyme to catalyze the hydrolysis of CO_2 without enzyme drawbacks
- Achieve capture with fast kinetics and lower binding energy
- Optimize catalyst placement at the gas-liquid interface
- Enable innovative system designs

High performance MOF/polymer composite membranes for carbon dioxide capture

Schematic of a single hollow fiber



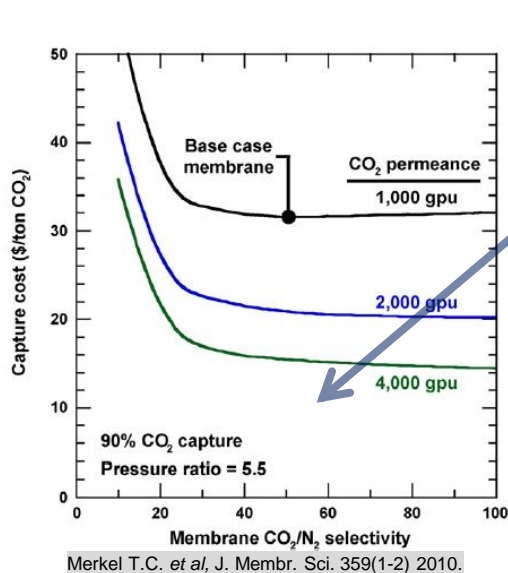
SEM image of MOF nanoparticles prior to inclusion in polymer matrix

Our two year program at Georgia Tech will address the key challenges in making MOF/polymer membranes poised for commercialization.

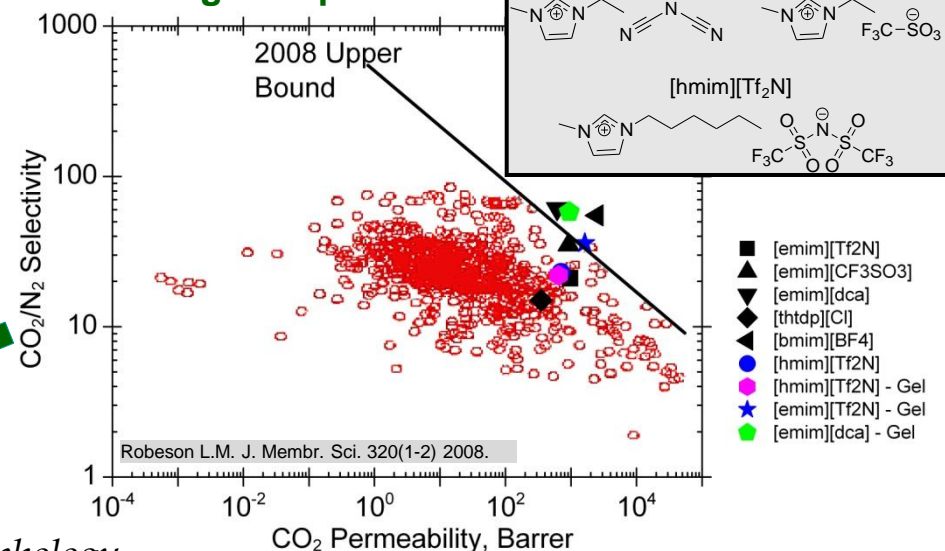
Technical challenges to fabricate high performance MOF/polymer composites:

- Select best MOFs from thousands of potential candidates (via high throughput computation)
- Select MOFs with exception robustness to moisture and trace contaminants (via high throughput experiments)
- Synthesize target MOFs in nanoparticle form and optimize polymer/MOF compatibility
- Select best MOFs for membrane operation (via experiments with cast polymer films)
- Optimize fabrication of MOF/polymer fibers (via experiments with hollow fibers)

Achieving a 10,000 GPU Permeance for Post-Combustion Carbon Capture with Gelled Ionic Liquid-Based Membranes



RTILs have promising permselectivity character and tolerance to flue gas impurities



Challenge:

Material stability: SLM format limitations

Enhancing permeability thru chemistry & molecular morphology

Approach:

Tailored gel-ILs, RTIL/poly(RTIL) composites, incorporation of task specific complexation chemistries

Challenge:

Enhancing permeance through selective layer thickness (SL) minimization

Approach:

Commercially viable fabrication technique development using ultrasonic spray coating technology (USCT) -- enabling controlled ultra-thin SL deposition on commercially attractive support platforms



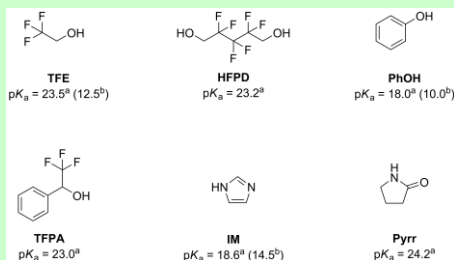
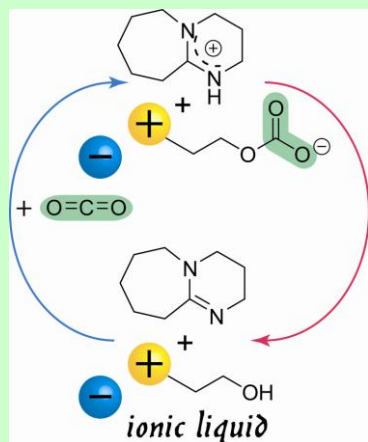
Membrane Permeance 10,000 GPU & Selectivity > 20

High Performance CO₂ Scrubbing Based on Hollow Fiber-Supported Designer Ionic Liquid Sponges

Dr. Sheng Dai Oak Ridge National Laboratory

Technology Summary

Our preliminary work at ORNL has demonstrated we can overcome alcohol volatilization obstacles of current liquid-based CO₂ capture technologies by two interrelated approaches: (1) integrating alcohol functionalities into the structures of ionic liquids and (2) developing new classes of protic ionic liquids whose anions are CO₂-binding strong bases. These two approaches can completely eliminate the use of volatile *n*-alkanols and water. Nonvolatility coupled with fast CO₂ sorption kinetics is expected with the nascent ORNL CO₂ capture approaches. Our emergent catch-and-release system has the potential to considerably cut the cost and energy associated with gas uptake and release meanwhile making CO₂ capture technologies commercially viable on a large scale. These scientific advances will also ensure the United States maintains a technological lead in developing and deploying advanced energy technologies.



Key Personnel

Dr. Sheng Dai, Oak Ridge National Laboratory (ORNL); Dr. Huimin Luo (ORNL); Dr. Gary A. Baker (ORNL); Prof. William J. Koros (Georgia Institute of Technology); Dr. Val Golovlev (Sci-Tec)

Program Summary

Period of performance: 24 months

	Key Milestones & Deliverables
Year 1	<ul style="list-style-type: none">Develop methodology for synthesis of task-specific Develop methodology for synthesis of alcohol-functionalized ionic liquids.Demonstrate that adsorption and desorption kinetics meet the operation criteria.Downselect alcohol-functionalized ionic liquids for carbon capture.
Year 2	<ul style="list-style-type: none">Develop methodology for synthesis of task-specific protic ionic liquids based on superbases.Identify lead compositions of protic ionic liquids for carbon capture.Demonstrate long-term stable operations in membrane test.

Technology Impact

The most effective approach for carbon capture involves chemical absorption by an aqueous solution of an *n*-alkanol, such as monoethanolamine. The intrinsic deficiency associated with this capture technology is the evaporative loss of the active solvent system, resulting in significantly increased operation cost and sophisticated process requirement. The success of this project will eliminate this key deficiency associated with our current liquid carbon-capture system, leading to a less costly and environmental friendly process.

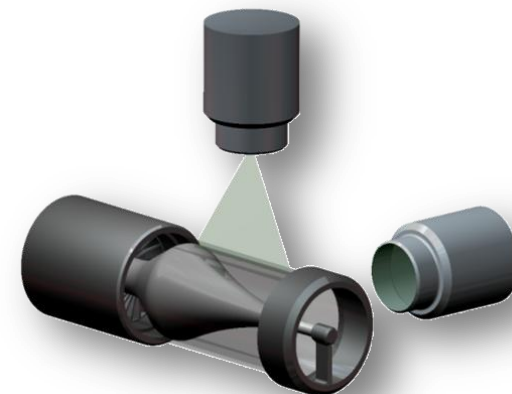
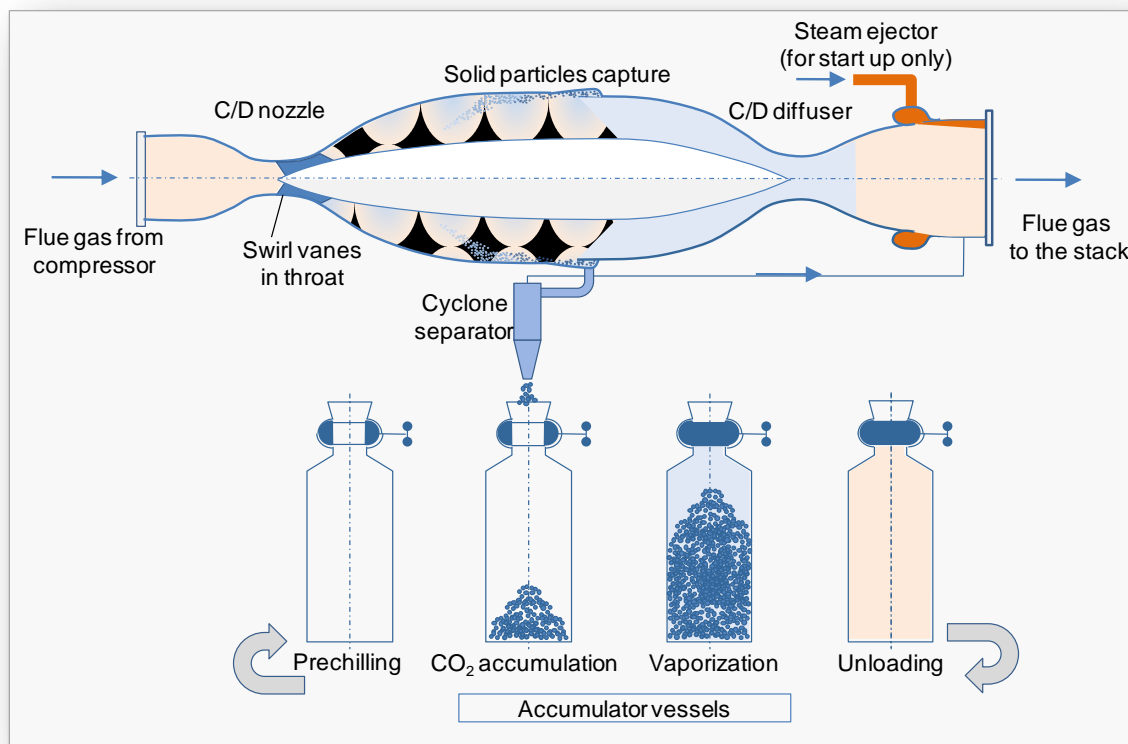
Cost and energy cutting CO₂ catch-and-release system based on designer ionic liquids



Introduction of the ICES Project

Aerospace/defense contractor **ATK** and small business **ACEnT Labs** are developing Inertial CO₂ Extraction System (ICES) based on rocket nozzle and wind tunnel applications.

This technology offers the potential for the lower COE increase and simplified integration with the existing power plants. ICES process comprises the steps of : swirling/expansion/cooling in convergent/divergent nozzle, CO₂ desublimation/precipitation, solid CO₂ particles capture and accumulation, CO₂ self-pressurization through sublimation back to the gaseous phase.

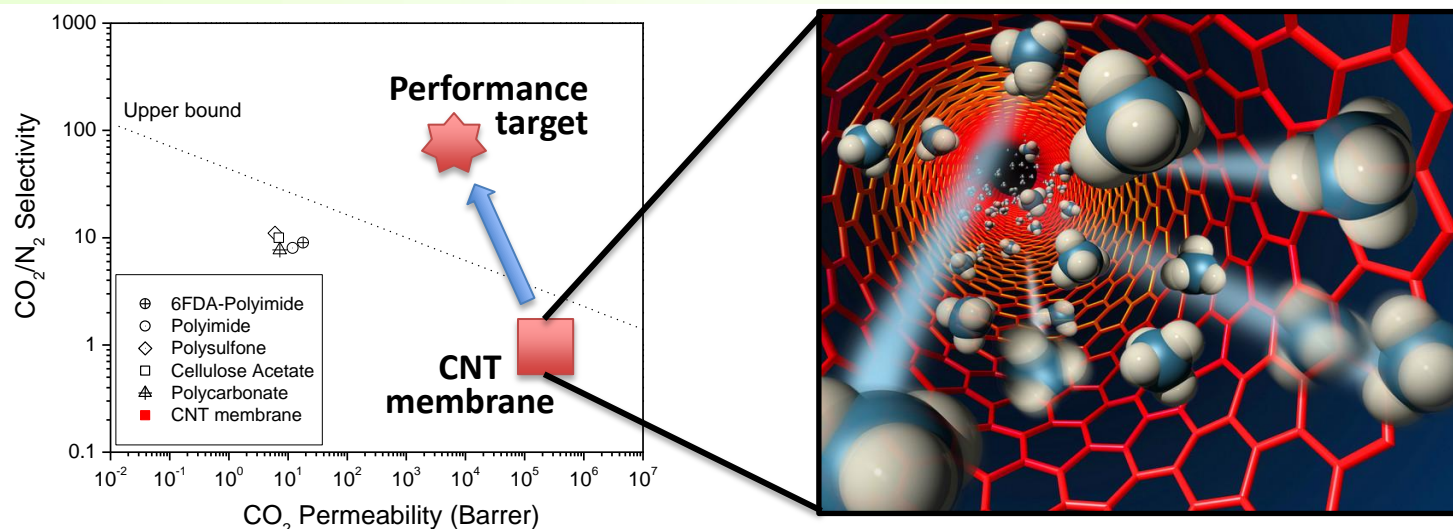


Carbon nanotube membranes for carbon sequestration

Porifera, Inc., Hayward, CA (with LLNL and UC Berkeley)

Membrane-based CO₂ capture is more efficient and more economical than the current amine-based process.

Membranes with CNT pores enable membrane-based capture as they overcome the current “upper bound” limitation of membrane performance

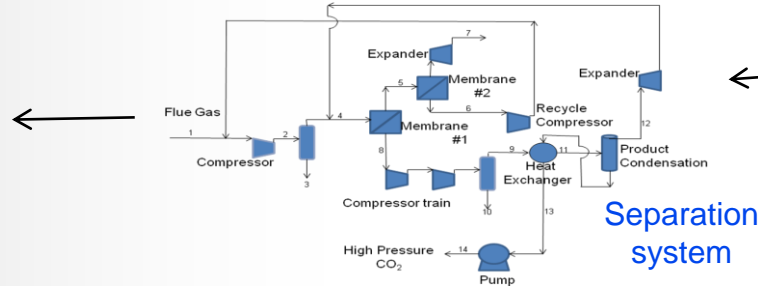
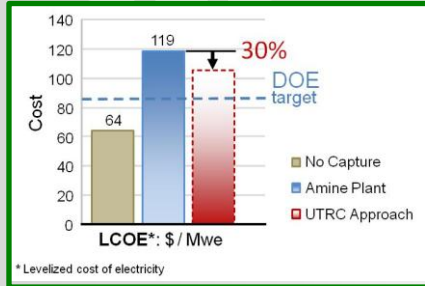
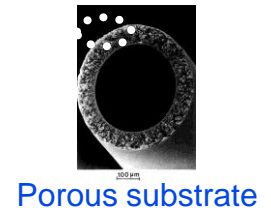
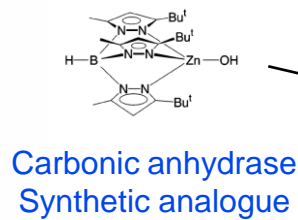
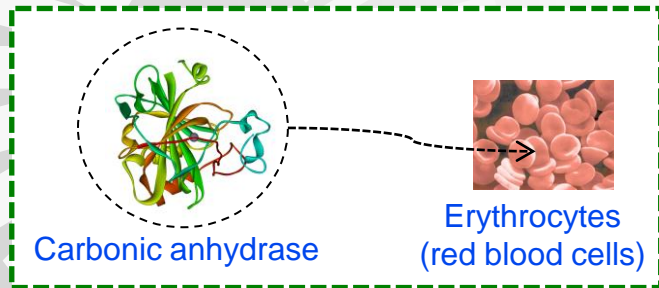


- Sub-2-nm carbon nanotube pores support gas fluxes **>100x of the pore of similar size**: much higher permeability than conventional gas membranes
- Membrane functionalization increases CO₂/N₂ selectivity and lowers overall flux...**but we can afford it!**
- Final goal: **CO₂/N₂ selectivity>100, Permeability>10⁴ barrer**
- Estimated technology impact: **>savings of \$10B/yr**



Porifera

CO₂ Capture with Enzyme Synthetic Analogue



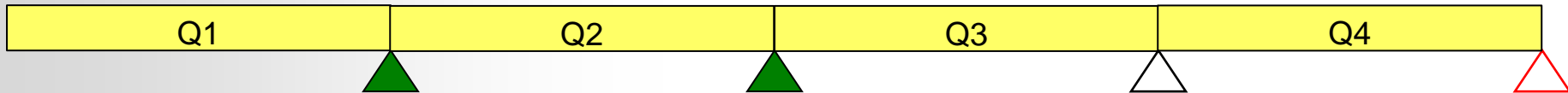
2010

Membrane prop.
mapping

Atomistic model
verification

≥3 paths
to films

No unrecoverable
poisoning



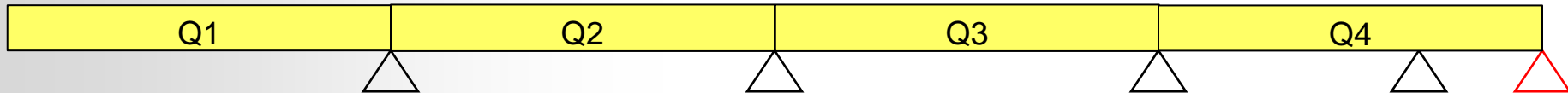
2011

Three model
films prepared

Selectivity improvement
demonstration

≥100 selectivity
≥ permeance

30% cost reduction
vs. amines



≥200 hr
durability test

Resin Wafer-Electrodeionization for Flue Gas Carbon Dioxide Capture

A new strategy for CO₂ capture:

- **Addresses CO₂ absorption & release**
 - Resin Wafer-Electrodeionization designed and developed to capture and release CO₂ (CO₂_RW-EDI)
 - Kinetics enhanced with carbonic anhydrase enzyme
- **Employs electrochemical pH control**
 - pH shifts capture and release CO₂ in separate cells
 - Water splitting enables in-situ pH control for optimum activity
 - Eliminates the need for acids and bases
- **Decreases parasitic energy load**
 - Avoids temperature and/or pressure swings for regeneration
 - Avoids the use of steam and vacuum



Electric Field Swing Adsorption for Carbon Capture Applications

Award DE-AR-0000026: Chemistry Department, Lehigh University

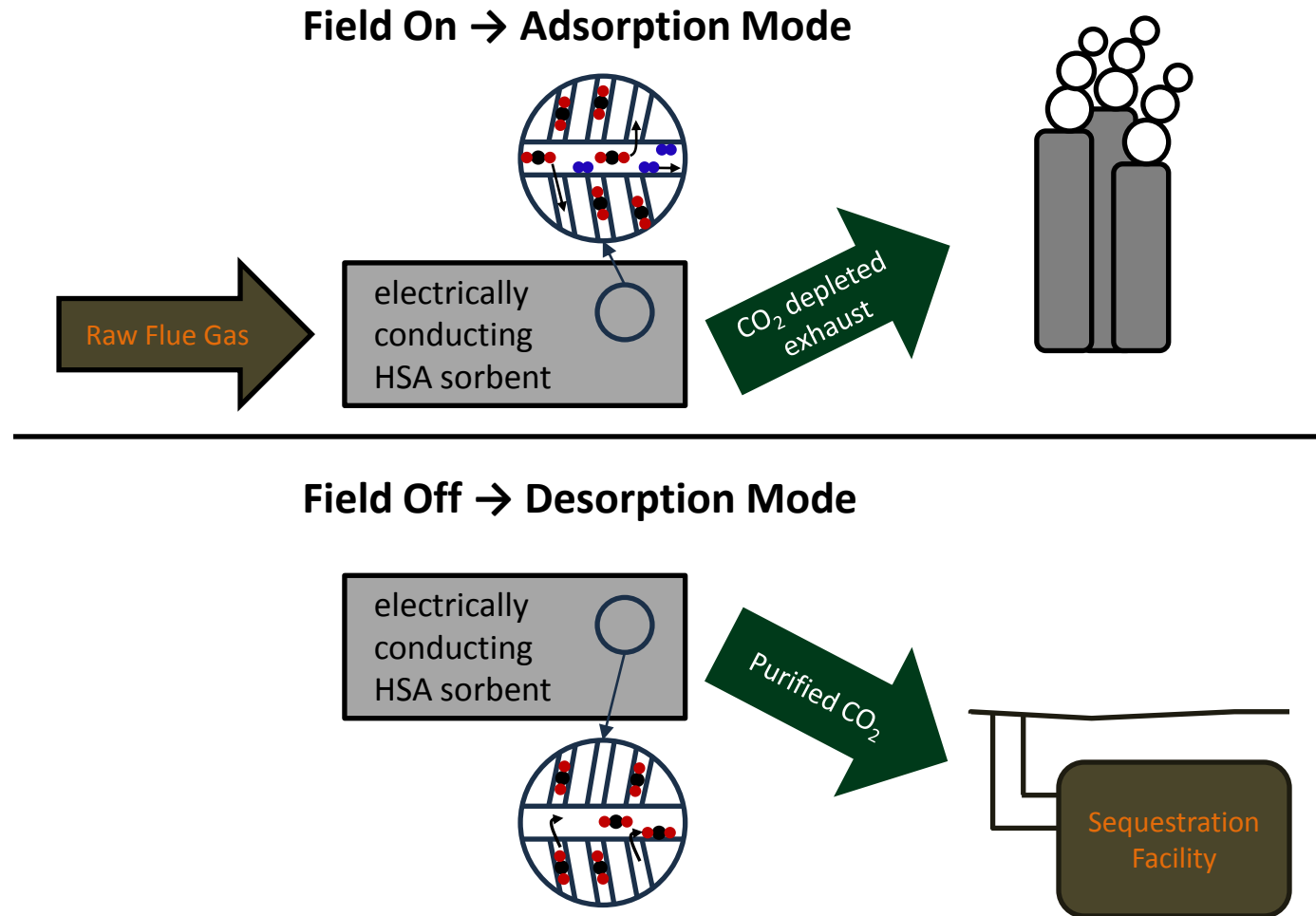


Use applied electric fields to control thermodynamics of CO₂ adsorption

•Simplicity

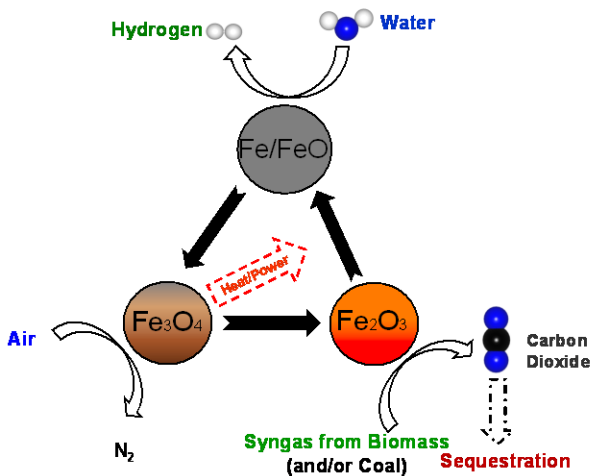
•Reversibility

•Efficiency



Pilot Scale Testing of the Carbon Negative, Product-flexible Syngas Chemical Looping Process

Led by Prof. Liang-Shih Fan (PI)



SCL Concept – Integrated CO₂ Capture



OSU Sub-Pilot SCL Facility



- **Novelty and Readiness of the Proposed Technology**
 - 10 – 20% improvement for power generation, hydrogen production, and liquid fuel synthesis with nearly 100% CO₂ capture
 - Successful bench and sub-pilot scale demonstrations
- **Project Objectives**
 - Pilot unit design and construction at NCCC
 - Long term continuous operation
 - Validate the techno-economic attractiveness of SCL
- **Potential Impacts**
 - GHG Emission Reduction
 - Energy Efficiency Enhancement
 - Energy Security Improvement
- **Budget**
 - \$5 million from DOE ARPA-E
 - \$4.9355 million cost share
- **Project Status**
 - (On Time) Full size cold model construction and shakedown completed
 - (On Time) Preliminary P&ID for hot unit completed

